History and Implications of Emerging Transactive Energy Systems

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Global energy goals cannot be met without changes in how we control complex systems

Energy systems
- Potential for substantial efficiencies in end-use systems with new controls
- More data and devices available
- New assets difficult to coordinate
- Existing controls antiquated

Cyber-physical systems
- Growing “edge” computing resources
- Cloud computing becoming paradigm
- Existing security models challenged

Traditional centralized control approaches are a common weakness
Types of Smart Grid Coordination

► **Direct (Top-Down) Control**
  - Utility switches devices on/off remotely
  - No local information considered

► **Central Control/Optimization**
  - Optimization and control from a central point
  - Relevant local information must be communicated to central point

► **Price Reaction Control**
  - Prices signalled to customers and/or their automated devices
  - No communication of local information

► **Transactive Energy (TE)**
  - Automated devices engage in market interactions
  - Information exchange includes quantity (e.g., power, energy) and price

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Slide produced with permission from Dr. Koen Kok, *The PowerMatcher Smart Coordination for the Smart Electricity Grid*, published by TNO, The Netherlands, 2013. [www.tinyurl.com/PowerMatcherBook](http://www.tinyurl.com/PowerMatcherBook)
What is Transactive Energy?

“system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter.”

[GridWiseTransactive Energy Framework (2015)]
A Taxonomy of Transactive Systems

Foundation in Economics

Distributed, Constrained Economic Power Flow

- Simple
- Intuitive
- Facilitates DER planning
- Clear transactions

Auctions

- Field experience
- DER control
- Dynamic
- Market clearing process
- Intrinsic transport

Bilateral Trades

- Simple
- Intuitive
- Facilitates DER planning
- Clear transactions

Foundation in Physics

- Constrained power flow
- DER & resource control
- Dynamic
- Very distributed
- Extensible
## Transactive Energy Principles

<table>
<thead>
<tr>
<th>Principle</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>Highly automated, coordinated self-optimization</td>
<td>Provide non-discriminatory participation by qualified participants</td>
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<td>Transacting parties are accountable for standards of performance</td>
<td>Observable and auditable at interfaces</td>
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<td>Maintain system reliability and control while enabling optimal integration distributed energy resources</td>
<td>Scalable, adaptable, and extensible across a number of devices, participants, and geographic extents</td>
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**Principles:** High-level requirements for TE systems that provide an additional point of reference for communicating with stakeholders and identifying common ground within the transactive energy community.

From GridWise Architecture Council’s Transactive Energy Framework: [http://www.gridwiseac.org/about/transactive_energy.aspx](http://www.gridwiseac.org/about/transactive_energy.aspx)
Some Transactive Energy Demonstrations

Olympic Peninsula demo, ca. 2006-07
- Established viability of transactive, decision-making to coordinate to achieve multiple objectives
  - Peak load, distribution constraints, wholesale prices
  - Residential, commercial, & municipal water pumping loads, distributed generation

AEP Ohio gridSMART® demo, ca. 2010-2014
- PUC-approved RTP tariff developed
  - Provides dynamic, real-time incentive to respond
  - Reflects real-time prices in PJM energy market
  - Manages AEP T&D constraints and peak load

Pacific NW Smart Grid demo, ca. 2010-2015
- Key advancements made by PNWSGD
  - Wind balancing
  - Developed look ahead signals
  - Formalized standardized definition of transactive node, test rig, etc.
  - Showed how “old school” approaches (e.g. direct load control) can be integrated with a transactive schema
Overview of a Transactive Auction Mechanism

1. Automated, price-responsive device controls express consumer’s flexibility (based on current needs)

2. Consumer system aggregates responses to form overall price flexibility curve

3. Service provider aggregates curves from all consumers

4. Aggregator determines price at which grid objective achieved, broadcasts to consumers

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Price-Discovery Mechanism

Supply Limit

Load (kW)

Q_capacity

Aggregate Demand Curve (all consumers)

P_clear

Price ($/kWh)

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Consumer Price-Flexibility Curve*

Max Load

Charge battery

AC

Base Load

Discharge battery

Water heater

Price ($/kWh)

* Labels removed before sending to utility
**Transactive Thermostat Control**

- **Price**
  - $P_{\text{average}} + k_{T_H} \sigma$
  - $P_{\text{bid}}$
  - $P_{\text{average}}$
  - $P_{\text{clear}}$

- **Temperature**
  - $T_{\text{min}}$
  - $T_{\text{set, a}}$
  - $T_{\text{set}}$
  - $T_{\text{current}}$
  - $T_{\text{max}}$

- **Graphical Representation**
  - Bid price
  - Bid curve
  - Average price
  - Market price
  - Min. temp. limit
  - Adjusted set point
  - Desired temperature
  - Current zone temperature
  - Maximum temperature limit

(cooling mode example)
Price-Based Distribution Dispatch

- Unresponsive loads (control/fixed/TOU res, and large unmanaged commercial loads)
- Large commercial customers with asynchronous DG or managed loads
- First synchronous DG unit
- Second synchronous DG unit
- Residential RTP customers

Feeder

$P_{\text{clear}}$

$Q_{\text{clear}}$

Price ($/\text{MWh}$)

Quantity (kW)
Pacific Northwest Smart Grid Demonstration (PNWSGD) Project

What:
• $178M, ARRA-funded, 5-year demonstration
• 60,000 metered customers in 5 states

Why:
• Develop communications and control infrastructure using incentive signals to engage responsive assets
• Quantify costs and benefits
• Contribute to standards development
• Facilitate integration of wind and other renewables

Who:
Led by Battelle and partners including BPA, 11 utilities, 2 universities, and 5 vendors
PNWSGD Demonstration Region
Basic Responsibilities of Nodes in the PNWSGD

\[
\text{Cost ($/MW)} = \text{function (Resources (MW))}
\]

\[
\text{function (Cost ($/MW))} = \text{Load (MW)}
\]

This exchange occurs at every “node” into a horizon of future time intervals.
Functional Elements of a Node

Toolkit
Functions, e.g., battery storage

Local Interfaces

External Interfaces

Asset System, e.g. Battery
Utility systems e.g. SCADA, DMS, etc

Transactive Feedback Signal
Transactive Incentive Signal

Neighbors Nodes
Transactive Interaction Model

Transactive Agent

- Optimize local business objectives
- Register and qualify capabilities to participate in others’ programs
- Judge terms & qualifications of others
- Bid for services needed, evaluate & accept offers from supplier(s)
- Value offers for services it renders, evaluate & accept bids from buyers
- Implement control of local assets under purview according to agreement
- Deliver & receive products, rights, or service required by transaction
- Deliver & receive data, measurements & verification as required by transaction
- Execute financial settlement as required by transaction & reconcile performance differences

Registration/Qualification

Negotiation Process

Operations Process*

Measurement & Verification

Settlement/Reconciliation

One or more other Transactive Agents

Remote Data

Local Data

Local Control

Local Devices/Systems

Local Intelligence

Transactive Interaction

* E.g., operations signals or e-product exchange
Grid Friendly™ Appliance (GFA) Demonstration (Autonomous Devices)

- Autonomous GFA under frequency curtailment response to 200 appliances in 150 residences
  - 150 Whirlpool/Sears dryers
  - 50 water heaters
- Assess performance through correlation with frequency events
  - Event log & load data collection (Invensys)
- Assess consumer acceptance – Whirlpool post-survey

“When the inevitable occurs ... people get stuck in elevators and high-value uses of power are shut off along with all the lowest priority uses of energy. It's the meat-ax approach to interrupting power flows.”

Dr. Vernon Smith, 2002 Nobel prize Winner, Economics
Small Appliances?

This is the world’s first Grid Friendly™ frequency-responsive coffee maker. Which appliances are too small to participate in grid reliability services?
Autonomous Frequency Regulation

Control Surfaces

Control Frequency Distribution Envelopes

Measured Frequency Distributions

Integrated Fractional Distribution
Implications for Power Electronics

- Devices are getting smarter → Controls
- System is getting more collaborative → Communications
- Systems are more dynamic → Resiliency
- Control is more distributed → Flexibility
- Rethink existing paradigms (DC power, microgrids) → Innovation
- Power electronic systems are being asked to do more → Opportunity
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